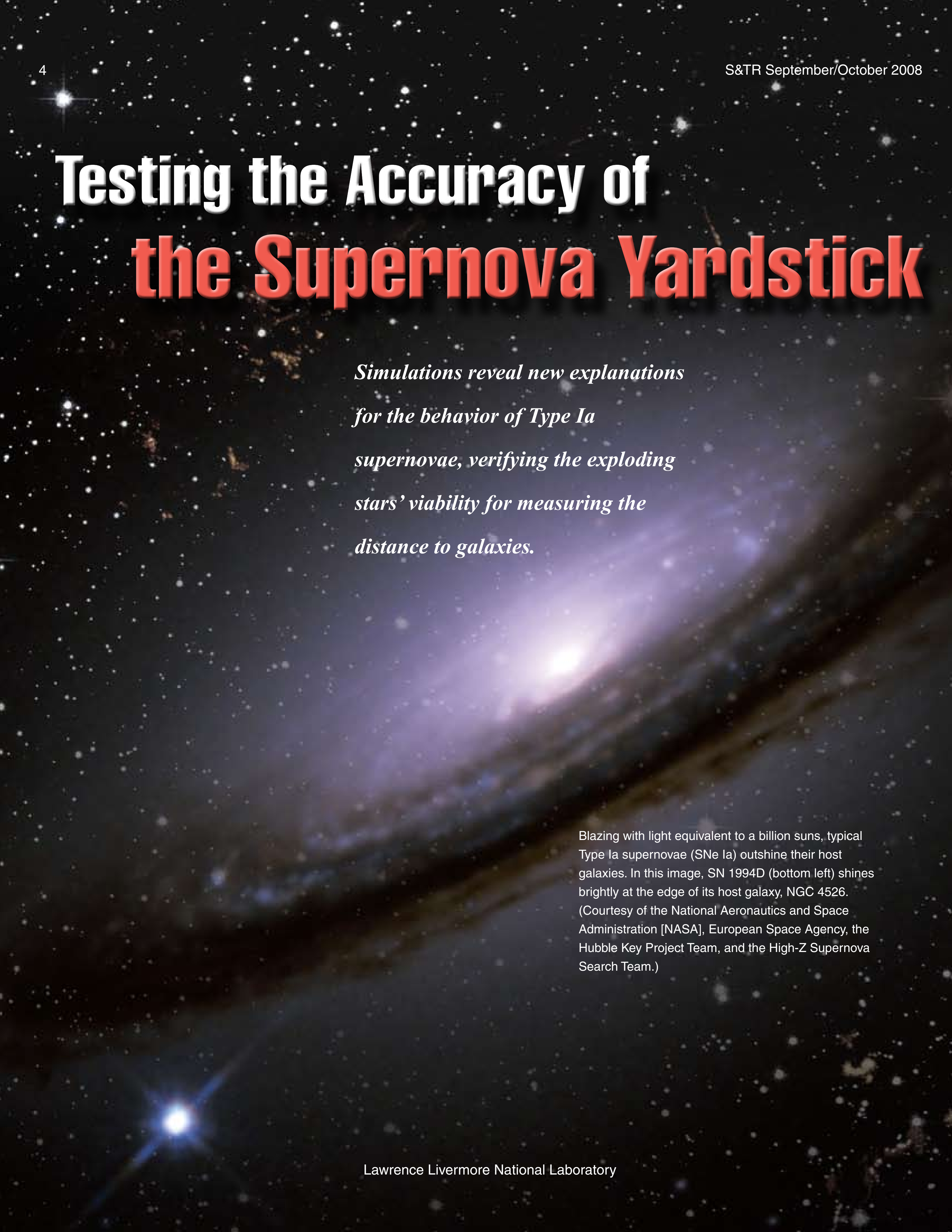
Testing the Accuracy of the Supernova Yardstick

Simulations reveal new explanations for the behavior of Type Ia supernovae, verifying the exploding stars' viability for measuring the distance to galaxies.



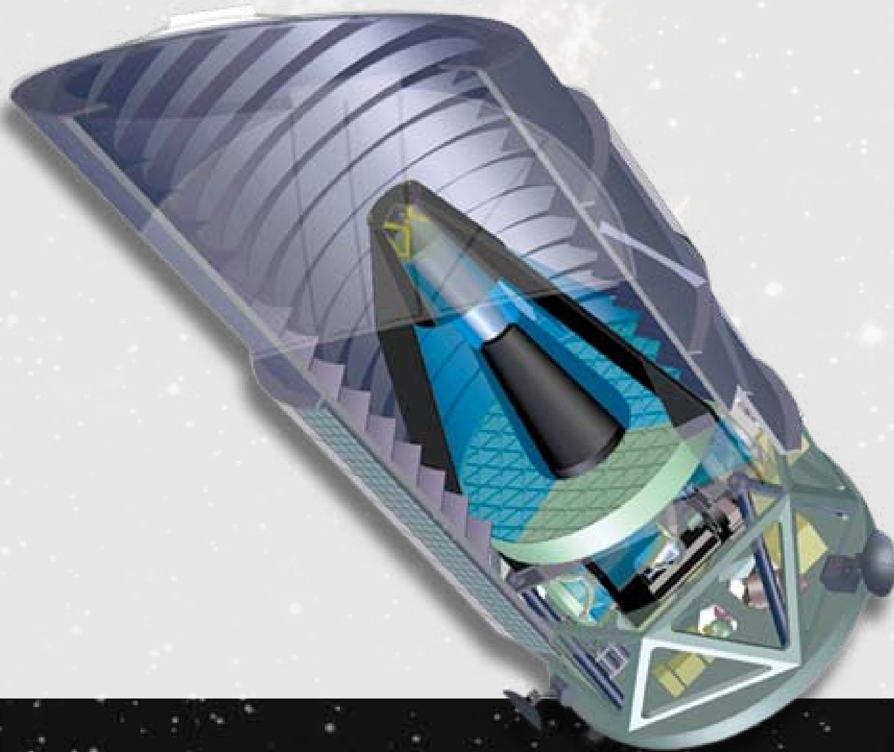
Blazing with light equivalent to a billion suns, typical Type Ia supernovae (SNe Ia) outshine their host galaxies. In this image, SN 1994D (bottom left) shines brightly at the edge of its host galaxy, NGC 4526. (Courtesy of the National Aeronautics and Space Administration [NASA], European Space Agency, the Hubble Key Project Team, and the High-Z Supernova Search Team.)

ASTRONOMER Edwin P. Hubble, for whom the Hubble Space Telescope is named, discovered in 1929 that the universe is expanding. Astronomical observations almost 70 years later revealed the startling news that not only is the universe expanding, but also the rate at which it is expanding is accelerating. Theories for the observed acceleration abound, and they differ in many ways. But all theories ascribe the acceleration to dark energy—matter of unknown composition that does not emit or reflect electromagnetic radiation and is therefore difficult to observe directly. Dark energy, which may constitute up to 70 percent of all matter and energy in the universe, is the greatest mystery in astronomy today.

News about the accelerating expansion, reported in 1998, was based on observations of exploding stars known as Type Ia supernovae (SNe Ia). (See the box on p. 9.) These thermonuclear explosions mark the death throes of white dwarf stars. SNe Ia are less common than Type II supernovae, which occur from gravitational collapse. Because most SNe Ia are observed to have quite similar characteristics, astronomers have used them as "standard candles," which serve as "yardsticks" for calculating the distance to their host galaxies from Earth. Using the calculated distances and observed velocity (determined by the red shift of the light), cosmologists gauge the degree of acceleration of these galaxies and, by extension, the influence of dark energy.

The Department of Energy (DOE) Office of Science has identified "dark energy and the search for genesis" as one of its top priorities. Fusion energy, advanced computing, and nuclear matter at the extremes are among others. Solving the mystery of dark energy is a key component of *Quantum Universe: The Revolution in 21st-Century Particle Physics*, a recent report from the Office of Science and the National Science Foundation that identifies the most compelling questions facing contemporary particle physics research. DOE and the National Aeronautics and Space Administration (NASA) plan to launch the SuperNova Acceleration Probe (SNAP) before 2020 to more precisely measure the expansion of the universe and to investigate the nature of the dark energy accelerating this expansion. SNAP is one of several Earth- and space-based missions planned over the next 15 years to quantitatively observe supernovae, examine dark energy, and better understand the beginning and possible future of our universe.

The application of SNe Ia as standard candles for determining distances to galaxies has revolutionized cosmology, giving astronomers an essential tool to extend their knowledge of the universe's expansion and acceleration. However, that



The SuperNova Acceleration Probe (SNAP) is a proposed space-based observatory that would locate and analyze thousands of SNe Ia each year. SNAP is part of the Joint Dark Energy Mission, a cooperative venture between NASA and the Department of Energy. (Image courtesy of Lawrence Berkeley National Laboratory.)

knowledge depends on the assumption that all SNe Ia are truly "standard." Does each explosion provide the same intrinsic brightness? With the planned space missions, the number of observed SNe Ia is expected to increase from a few thousand to hundreds of thousands in the near future. Accurately understanding the behavior of SNe Ia is essential to making the investments in science pay off.

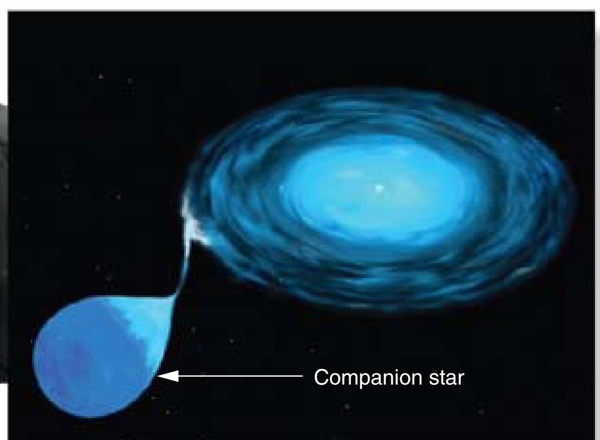
Birth of a Candle

Nearly all of the SNe Ia identified to date have been observed with ground-based telescopes. This sampling thus consists mostly of nearby SNe Ia, which are fairly young. The older, more distant SNe Ia are dimmer and more difficult to observe and may explode differently than nearby SNe Ia. Livermore nuclear physicist Rob Hoffman led a collaboration that used one of the world's largest supercomputers for simulating the physical processes underlying the explosions of SNe Ia to understand their similarities and differences.

The study was a part of Livermore's Computing Grand Challenge Program, which allocates millions of central-processing-unit (CPU) hours on Laboratory supercomputers to unclassified projects that support Livermore's missions. The supernova simulations were performed by the Computational Astrophysical Consortium (CAC), with members from the University of California at Santa Cruz, Lawrence Berkeley National Laboratory, State University of New York at Stony Brook, and Lawrence Livermore. The team was allocated 4 million CPU hours on Atlas, one of Livermore's workhorse supercomputers for unclassified research. Previously, the team had used supercomputers at Oak Ridge National Laboratory, the National Energy Research Scientific Computing Center at Lawrence Berkeley, and NASA Ames. Likening these supercomputer resources to a baseball lineup, Hoffman says, "Atlas is our 'cleanup' hitter, not because it is a particularly heavy hitter—they all are—but because it gets a hit every time."

SNe Ia evolve from a complex of two stars, in which a dead stellar core called a white dwarf accretes material from a companion star. As the white dwarf collects more material, it becomes denser and hotter. Eventually, conditions become so extreme that carbon atoms fuse and ignite one or more miniscule nuclear flames, which erupt near the center of the dwarf. A runaway thermonuclear reaction ensues that disrupts the entire white dwarf, creating an extremely bright optical display that is visible billions of light years away. For a few weeks, SNe Ia are so bright they outshine their host galaxies. "Astrophysicist Subrahmanyan Chandrasekhar, who made enormous contributions to the study of stellar structure and dynamics, showed theoretically in the 1930s that a white dwarf could grow no larger than 1.38 solar masses before it would explode," says Hoffman. "An exploding white dwarf burning a significant fraction of this mass provides the observed luminosity. A strong argument for using SNe Ia as standard candles is their initial identical configurations."

A Type Ia supernova explosion generates a light curve, which is quite similar for nearly all SNe Ia. The brightness of a typical Type Ia supernova peaks about 20 days after the explosion, after which the light curve follows almost exactly the radioactive decay curve for nickel-56, an isotope that decays to iron. Although the light curves of all SNe Ia



(Right) An artist's conception of a Type Ia supernova precursor system depicts a companion star accreting material through an accretion disk onto a dead stellar core composed of carbon and oxygen, called a white dwarf. (Drawing courtesy of Space Telescope Science Institute and NASA.) (Left) In 1931, astrophysicist Subrahmanyan Chandrasekhar showed theoretically that a white dwarf would explode as a supernova when its mass exceeded what is now called the Chandrasekhar limit (1.38 times the mass of our Sun). In 1983, Chandrasekhar, along with William Alfred Fowler, was awarded the Nobel Prize in Physics in part for this work.

exhibit a similar pattern, they do differ in peak brightness and the brighter ones (with higher peaks) are wider.

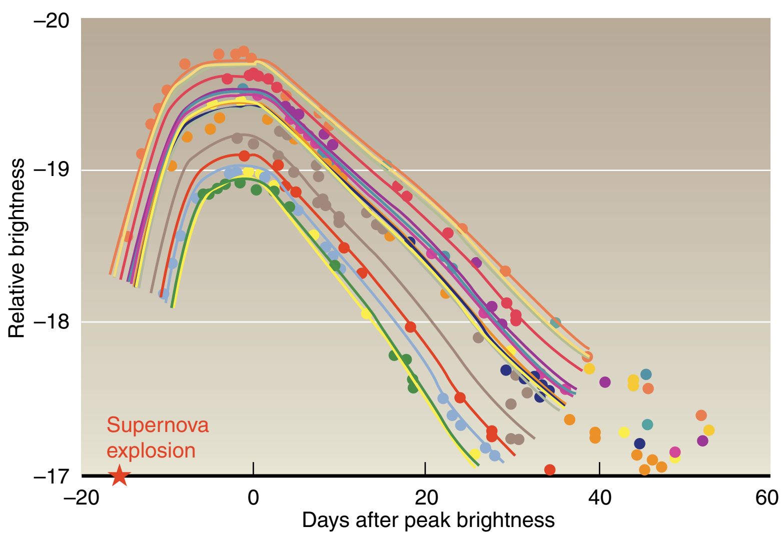
Astronomers use a technique that reduces all SNe Ia light curves to a single width–luminosity relationship. In this way, all SNe Ia can be considered as a single parameter family. The width of a light curve indicates the supernova's intrinsic brightness, according to the rule "broader is brighter." Also similar are the emission spectra sampled at specific times after peak brightness, lending yet more credence for use of SNe Ia as standard candles. The spectra of SNe Ia indicate the presence of silica, sulfur, calcium, and nickel-56. "About one-third of all iron in the universe, and by inference the hemoglobin in our blood, comes from these exploding white dwarfs," says Hoffman.

A major goal of the team's simulations is to better understand the width–luminosity relationship. In particular, scientists want to rule out the possibility that distant SNe Ia, formed in the earliest epochs of the universe, might explode differently from SNe Ia formed more recently. For example, the star-forming environment may have been different in the early universe because far fewer heavy elements were present. "We want to know if variations in initial conditions influence supernova brightness as we go back in time," says Hoffman. "If so, we would like to account for those variations to more accurately determine the distances, which would be required for the dark energy surveys. By accounting for variations, we can better use SNe Ia as standard candles."

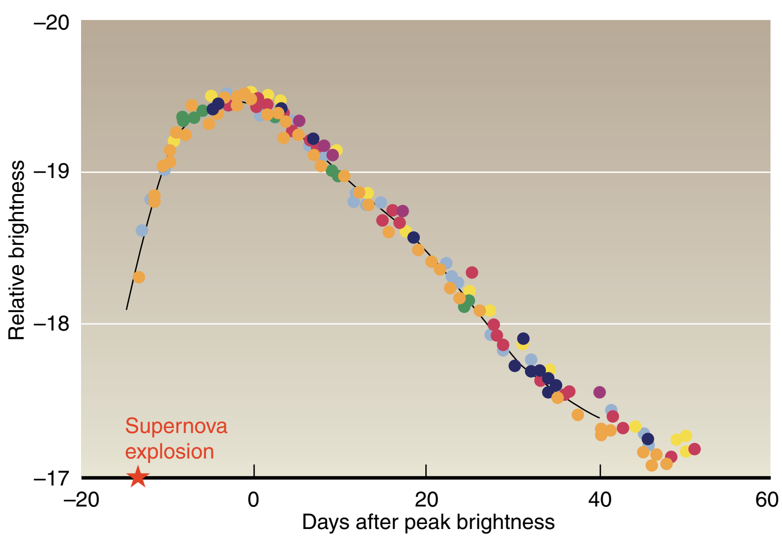
A Library for Observations

The CAC team's Grand Challenge effort, which ended in May, has resulted in a library of one- and two-dimensional models of SNe Ia with light curves and spectra. An astronomer spotting what appears to be a Type Ia supernova can compare its brightness, spectra, and light curve to the library data. Such a library will be particularly important because the planned DOE and NASA Earth- and space-based telescopes promise to discover tens of thousands of SNe Ia every year. Livermore scientists are helping design one of these telescopes, the Large Synoptic Survey Telescope, a ground-based, 8.4-meter device that will image faint astronomical objects. (See *S&TR*, November 2005, pp. 12–20.)

This same library of calculations and simulations also reveals for the first time why the amount of nickel-56 apparently controls the width of the light curve. Scientists have known for some time that the brightness of SNe Ia is determined by the amount of nickel-56 synthesized in the explosion. The decay of this radioactive



SNe Ia explosions exhibit similar light curves. In this graph, brightness is plotted against time before and after peak light (Day 0). Although the light curve patterns are similar, the brighter ones (top) are broader. Data are from the Calan–Tololo supernova survey.

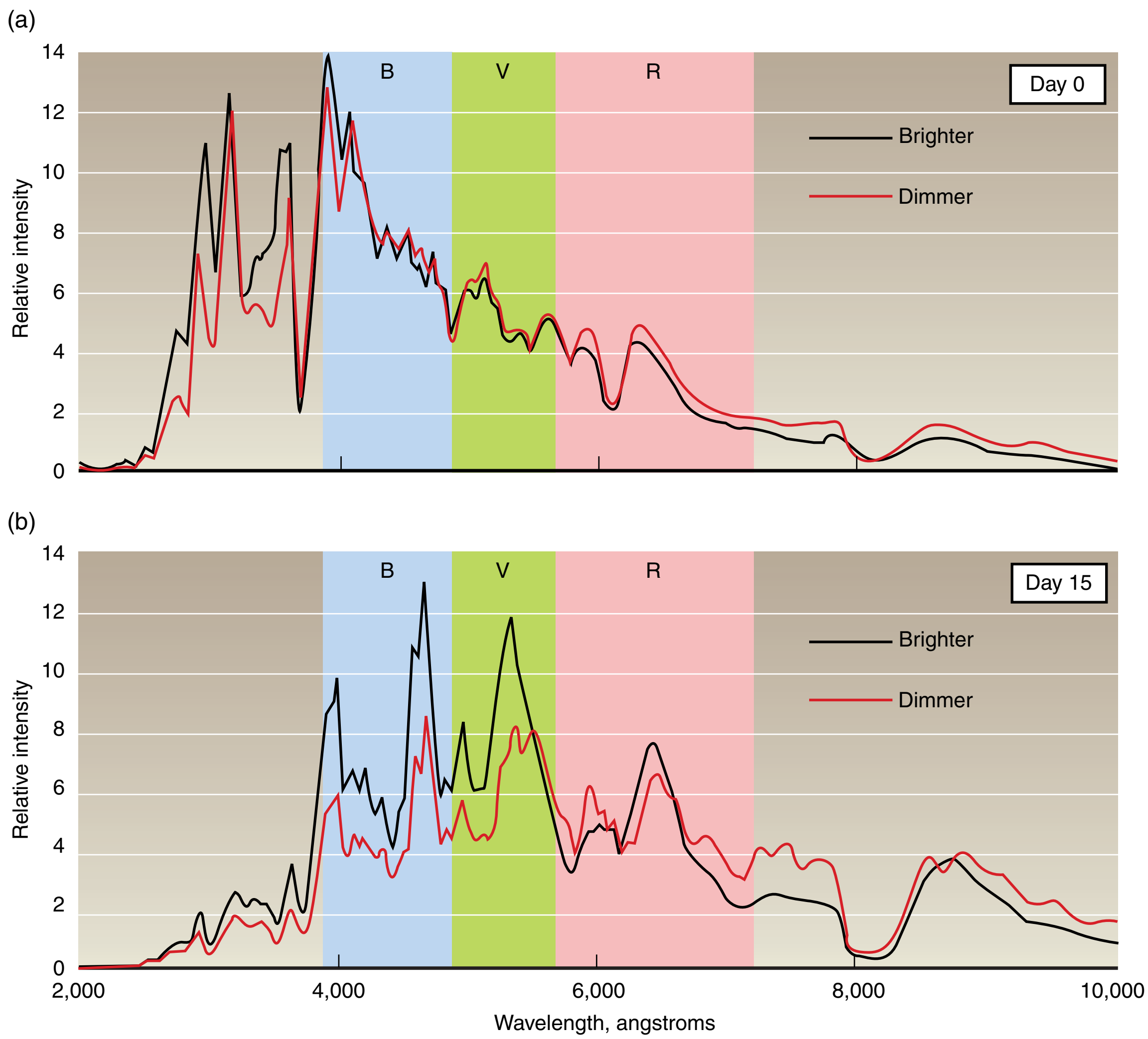


Astronomers use a technique that allows them to collapse SNe Ia light curves to a single curve so that the curves all obey a general width–luminosity relationship. The supernovae can thus be used as standard candles to infer the distance to their host galaxies.

isotope powers the luminous display. However, the problem of the light-curve width is challenging because the physics involves complex details of light transfer through the time-evolving, wavelength-dependent opacity of the supernova gas.

Because most SNe Ia have been observed from Earth, they have traditionally been seen through the electromagnetic spectrum of visual light. One of the team's important discoveries is that the width–luminosity relationship is most apparent in the color blue. Scientists are investigating how the color of supernova light evolves over time. Simulation results show that as supernovae iron-group elements (iron, cobalt, and nickel) cool, they exhibit a strong fluorescent effect, whereby light absorbed at blue wavelengths is reemitted at red and infrared wavelengths. The degree of fluorescence thus largely determines the color of the emergent supernova's spectrum.

Numerical models reveal that the fluorescence process is more efficient in lower temperature gas. Thus, as supernovae expand and cool, their color becomes increasingly red. In the dimmer supernovae, where the gas is initially cooler, this reddening effect evolves more quickly. When observed, the light curves of dim supernovae are found to drop rapidly. These findings are the basis of the width–luminosity relationship. "We are finding that not all SNe Ia are standard



The color of supernova light evolves over time. These graphs compare the evolution of a brighter supernova with more nickel (black line) and a dimmer supernova with less nickel (red line). Astronomers use the blue (B), visual (V), and red (R) filters to view specific ranges of the electromagnetic spectrum. The spectra have been superimposed so that they have the same intensity at about 4,200 angstroms. (a) At Day 0, both simulated supernovae have similar spectra. (b) By Day 15, light has shifted from the blue to red wavelengths as the supernovae expand and cool. In the dimmer supernova, this process happens more quickly and is responsible for the observed rapid decline of its light curve with time and hence the width–luminosity relationship.

candles," says Hoffman, "but most are within reasonable constraints."

Simulating Chaos

The evolution of SNe Ia is long and slow in the beginning, fast and furious in the middle, and then slow again in the end. For about a million years, the white dwarf accretes material from its companion star while its own core of carbon and oxygen becomes increasingly hot and dense. Eventually, convection takes over from conduction as the dominant cooling process, transferring heat from the center of the star outward toward the surface. When the buoyant material rises, shear forces generate turbulence, and nuclear energy from carbon burning increases exponentially as a function of temperature. That is, as the temperature rises, the amount of energy builds faster and faster, and the convection process alone cannot release this immense heat and energy. The temperature rises hundreds of millions of degrees over several hundred years. Suddenly, a nuclear flame ignites. The resulting explosion occurs in 1 second and is followed by a free expansion—an irreversible process in which gas expands without constraint. The expansion's light curve and spectra can be observed for up to 100 days.

Many uncertainties remain regarding the evolution of a white dwarf to its full expansion and the observed variation in brightness. Still not clearly understood are the strong convection currents leading to the formation of hot spots that ignite the flame, the propagation of turbulent nuclear burning through the star, the explosion itself, the accompanying synthesis of new elements, and the light curve and spectra emitted from the explosion.

The Livermore simulations, however, did address several outstanding questions surrounding SNe Ia, each of which has eluded a solution for decades. These questions included whether the flame ignites at one or several points and whether it originates at or near the center of the dwarf. The simulations also showed how the flame propagates through the white dwarf, how it is affected by turbulence as it moves outward toward less dense regions, and how it may transition from subsonic to supersonic speeds.

Tools of the Trade

"No computer today is capable of modeling chaotic, submillimeter-scale phenomena occurring in an object 1,800 kilometers across over the course of 100 days," notes Hoffman. "The space and time scales differ too much." Separate models are needed to simulate each component. Modeling SNe Ia requires computer codes tailored to reveal the multiple aspects of the entire event. The collaborative team used a suite of codes developed for the

Evolution of a Type Ia Supernova

In a galaxy the size of the Milky Way, Type Ia supernovae (SNe Ia) occur about once every 50 years. Astronomers discover new supernovae in other galaxies at a rate of a few per week. New spacecraft and ground-based telescopes currently being planned are expected to increase the number of recorded supernovae seen yearly by many times.

SNe Ia begin as a complex of two stars. The first is a dead star, called a white dwarf, composed mostly of carbon and oxygen, the products of helium burning. This intrinsically faint star has a very small radius and high density. Its mass is about 0.6 that of our Sun, and its average radius is about 8,000 kilometers. The white dwarf's thermonuclear energy sources are extinct, and the star is in its final stage of evolution. Its companion star is either a young (main sequence) star, such as the Sun, or a middle-aged (red giant) star.

The white dwarf and its companion star orbit each other so closely that gravity from the white dwarf pulls material from the younger star onto its surface, a process called accretion. As the white dwarf reaches a mass 1.38 times that of our Sun (known as the Chandrasekhar limit), it can no longer support the bulk of its mass. Its central temperature and density rise to extreme conditions—300 million degrees and a density of 3 billion grams per cubic centimeter. Increasing temperature and density inside the core ignite carbon fusion as the star approaches its mass limit before exploding.

The explosion releases a tremendous shock wave, with star matter expelled at a velocity of up to 20,000 kilometers per second, or up to 10 percent the speed of light. An enormous increase in luminosity occurs. This extremely luminous object, 5 billion times brighter than our Sun, may outshine its entire host galaxy before fading from view over several weeks. During that short period, the supernova releases as much kinetic energy as the Sun will radiate in its entire lifetime.

After the explosion, a Type Ia supernova follows a characteristic light curve, the graph of luminosity as a function of time. This luminosity is generated by the radioactive decay of elements synthesized in the explosion—in particular nickel-56, which decays to cobalt and then to iron. About one-third of all the iron in the Milky Way Galaxy comes from exploding SNe Ia. These explosions can also trigger the formation of new stars and planets.

most part by Lawrence Berkeley and Lawrence Livermore.

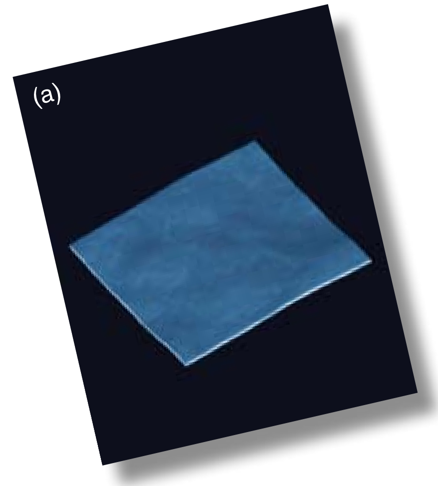
The code SNe is used to study the microphysics of nuclear flames and how these flames interact with turbulence. Another code, MAESTRO, incorporates the changes that occur as the dwarf begins to expand and release heat and as its hot core and less dense outer strata create buoyancy. Simulations from both codes concentrate on early events occurring at subsonic speeds.

When the thermonuclear explosion begins and materials start to move at supersonic speeds, the CASTRO hydrodynamic code takes over. Livermore has a long history of studying hydrodynamic behavior, which plays an important role in exploding nuclear weapons. In addition, the SEDONA code calculates the emergent spectra.

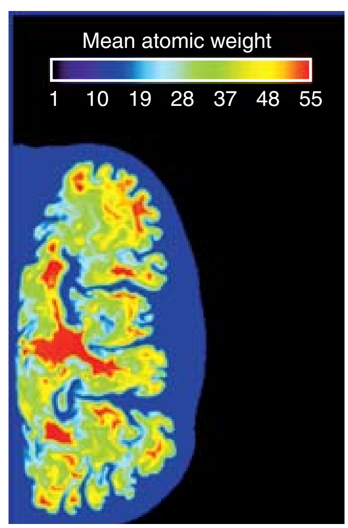
The team successfully combined these codes to model different phases of supernova evolution, ranging from the time when hot spots deep inside a dwarf's core give birth to the tiny nuclear flame to the weeks following the explosion. Various computer runs included modeling a white dwarf both in a stationary position and rotating at different speeds, the dwarf's initial flame igniting at different sites, flames burning at different speeds, and turbulence of varying amounts.

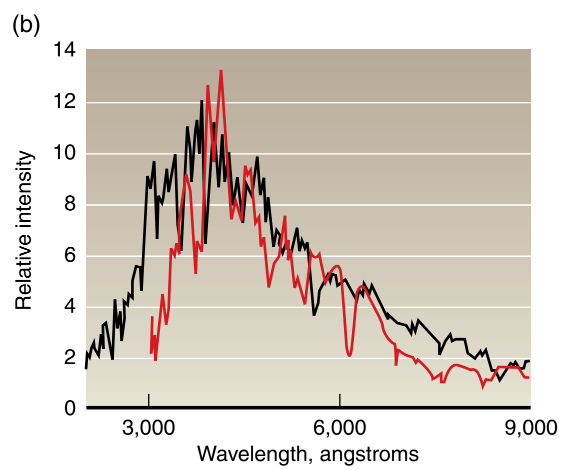
In two-dimensional simulations, a detonation with supersonic burning looks bright, and the spectra match most SNe Ia. If supersonic detonation and burning do not occur, the white dwarf explodes but is dimmer. Simulations showed that these spectra do not match those of most SNe Ia.

Scientists have debated whether an asymmetric explosion might modify both the luminosity and spectra of the material streaming out. The team's simulations of an asymmetric explosion produced the startling result that the peak brightness can vary with the viewing angle by nearly 40 percent. Therefore, if the spectra indicate an asymmetric explosion, one can mathematically correct for the brightness level.



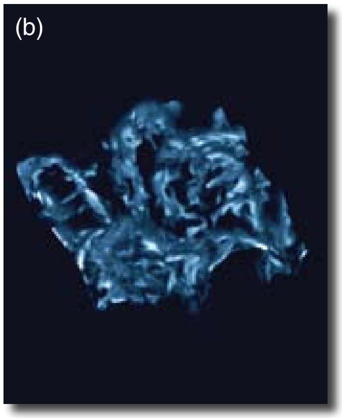
Simulation results show an initially thin nuclear flame—just 0.1 millimeter thick—moving through the dwarf's core, being pushed around by convective currents, and traveling at less than the local speed of sound. At first the flame remains fairly coherent. As it moves into regions of cooler and less dense fuel, turbulent motion deforms the flame, making it appear thicker and more wrinkled. At a critical point, the flame passes into the





(a) In this simulation, flames consuming a white dwarf remain subsonic throughout the explosion, exhibiting a dim supernova light curve. The nuclear burning produces a distribution of elements color-coded here by atomic weight (for example, blue is carbon and oxygen, green is silicon, and red is nickel). (b) The simulated spectrum (black line) reveals atypical features when compared with the spectrum observed in SN 1994D (red line). (c) When the turbulence is adjusted on the same model, the flame transitions to supersonic speeds after an initial subsonic explosion. This supernova produces 2.5 times more nickel, and hence, its brightness is much greater. (d) The spectrum of this simulated delayed detonation (black line) compares well to features observed in SN 1994D (red line).

(b)



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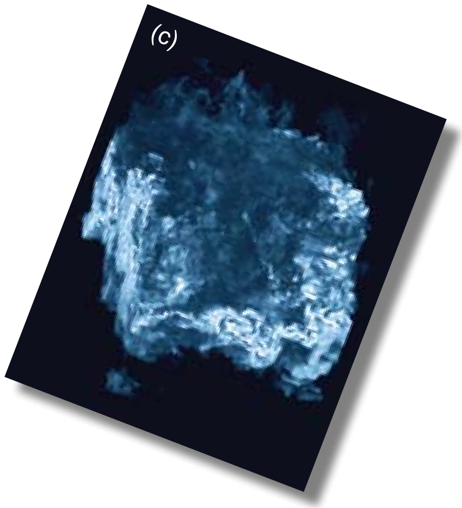
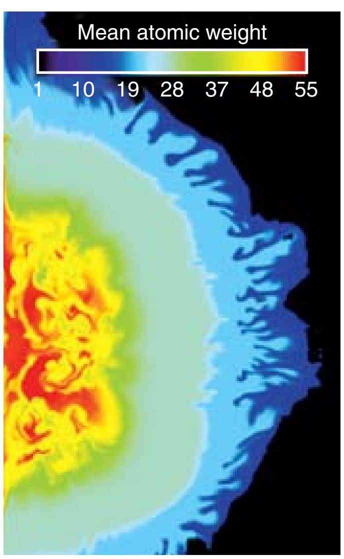


(a) In nuclear flame simulations, an initially thin (micrometer-wide) flame moves subsonically through a white dwarf's carbon fuel, releasing nuclear energy in the process. (b) As density decreases and turbulence increases, the flame enters a transitional stage in which it becomes extremely wrinkled. (c) Eventually, the flame enters the distributed burning regime, where it is shredded, its thickness and burning rate increase manyfold, and its velocity transitions to supersonic. At this stage, the flame is about 1 square meter. (Courtesy of Andrew Aspden of Lawrence Berkeley National Laboratory.)

so-called distributed burning regime, in which its thickness grows dramatically, its burning rate increases by a factor of five, and its speed transitions to supersonic. Hoffman notes that many aspects of the burning process are similar to those that drive the burning of fuel in an internal combustion engine. In fact, the simulation results have been aided by combustion modeling expertise of scientists at Sandia National Laboratories.

(c)



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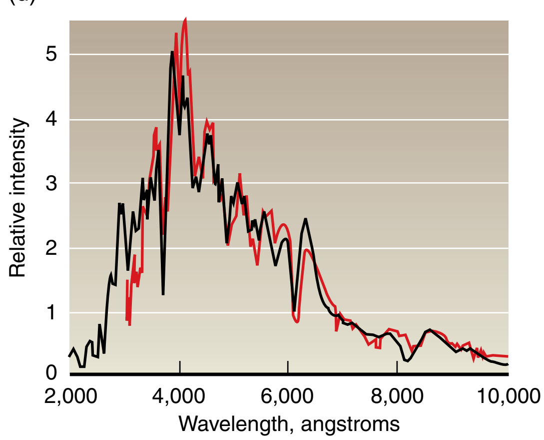

Uncovering the Truth

The CAC team plans to perform its first three-dimensional simulations of SNe Ia. The long-term goal is a continuous, end-to-end simulation, from the moments leading up to flame ignition to the weeks following the explosion. Such a comprehensive simulation is probably five years away and will require computational resources much larger than Atlas can currently provide.

Many questions remain, perhaps the most significant being why some SNe Ia are good standard candles while others are not. Livermore and other institutions will be examining additional aspects of SNe Ia, such as metallicity, the ratio of carbon and oxygen at the white dwarf's core, and binary properties that might be the cause of SNe Ia "outliers"—that is, those that do not conform to the width–luminosity relationship.

The findings from current and future observations, together with data from simulations, will also help astronomers and cosmologists determine if dark energy was stronger in the early universe and whether the expansion of the universe will continue to accelerate. "There are many theories and many conflicts but little guidance about the nature of dark energy," says Hoffman. "We're hoping our simulations will help uncover the truth."

—Arnie Heller and Katie Walter

Key Words: CASTRO code, Computational Astrophysical Consortium (CAC), cosmology, dark energy, Grand Challenge computing, hydrodynamics, MAESTRO code, SEDONA code, SNe code, Type Ia supernovae (SNe Ia).

For further information contact Rob Hoffman (925) 424-6411 (hoffman21@llnl.gov).